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Anomalous wavelength dependence of polarization of Comet 21P/Giacobini-Zinner

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Abstract

Results of CCD imaging and aperture polarimetry of Comet 21P/Giacobini-Zinner and Comet C/1989 U5 (Linear) are presented. Observations were carried out with the 2-m telescope of Pik Terskol Observatory and with the 0.7-m telescope of Kharkov State University in November 1998 and January 1999. The new observations and published data indicate an anomalous spectral dependence of polarization of Giacobini-Zinner, namely, a negative wavelength gradient of the degree of polarization. It is shown that this effect is not caused by the presence of molecular emission in the pass band of the employed filter. The uncommon spectral trend of polarization of Comet Giacobini-Zinner may be caused by a large content of organic matter in its dust or an overabundance of large particles as compared to the other comets.

Keywords: Comets; Polarization; Dust particles; 21P/Giacobini-Zinner; C/1998 U5 (Linear)

1. Introduction

Photometric and spectrophotometric data indicate that most comets are very similar to each other in chemical composition despite the fact that their relative gas and dust production vary widely. But there are exceptions. A'Hearn et al. (1995) have grouped the comets into normal and depleted ones. Comet 21P/Giacobini-Zinner belongs to the depleted group. It has low carbon/OH, NH/OH and NH_2/OH ratios.

Polarization can give some information about the composition and size distribution of solid particles and, therefore, it can complement spectrophotometry of cometary radicals in many respects. Most comets display similar polarimetric properties of their dust and consequently similar composition and size distribution of their dust particles. But what about the "depleted" comets? Do they differ from the normal comets also in their polarimetric properties?

In this paper we consider an uncommon behaviour of polarization of Comet Giacobini-Zinner. Contrary to all other comets, the wavelength gradient of the polarization of its dust is negative.

A single measurement obtained in 1985 and published in the summary paper by Chernova et al. (1993) shows the negative gradient of polarization of Giacobini-Zinner. Kurchakov et al. (1986) also measured the negative gradient in the comet. To clarify the issue, we continued the polarimetric study of this comet in 1998–1999. For comparison with a normal comet we also present polarimetric data of Comet C/1998 U5 (Linear) which was observed at the same time.

2. Observations and data reduction

CCD imaging polarimetry of Comet Giacobini-Zinner was conducted at the 2-m telescope of Pik Terskol Observatory (Northern Caucasus) on November 20, 1998 and

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January 25, 1999. Besides, on November 24, 1998 CCD polarimetry of Comet C/1998 U5 (Linear) was carried out. The two-channel focal reducer of the Max-Planck Institute for Aeronomy (Germany) was used with the four-beam Wollaston assembly as analyser as described by Geyer et al. (1996). With the two-channel system polarimetric measurements can be performed simultaneously in two wavelength intervals (Jockers et al., 1997). A new Wollaston prism with a splitting angle of 2° was used. A single field stop with a field of view of 103 × 103 arcsec was used. Polarizing foils used in conjunction with the Wollaston prism allowed to obtain individual flat fields for the four polarization directions. The observations were conducted with the narrow-band continuum filters 4430/44 and 6420/26 Å. The Metcalf method was used to compensate for the proper motion of comet. Five standard stars with zero polarization and three stars with large polarization were observed to determine the parameters of instrumental polarization.

The CCD images were processed using the MIDAS reduction package. The image processing included bias correction, flat field division, removal of cosmic ray events, the determination of the polarization parameters of the instrumental system, the alignment of subimages with different polarization directions, and the construction of polarimetric images.

After correction for instrumental polarization the observed polarization degree of the polarized standard stars deviates from the catalogue values by 0.3 ± 0.2% and the position angle of the plane of polarization by 1°.

Comet Giacobini-Zinner was also observed with the 70-cm reflector at the Chuguev Observation Station of Kharkov State University on November 19–22, 1998. A photopolarimeter with a fast-rotating polaroid was used (Kiselev and Velichko, 1998). The comet was observed at large air masses and was somewhat faint for this telescope. That is why we used only the wide-band filter 7228/1140 Å and an 88 arcsec diaphragm. Each set of measurements of the comet contained four integrations taken with an exposure time of 30 s. Four measurements of sky background were made before and after the comet. Several sets of measurements were obtained. The instrumental polarization and zero-point of the polarization plane were determined from observations of standard stars with zero and large polarization, respectively. Instrumental polarization, which does not exceed 0.1%, was subtracted from the cometary data. Apart from November 22, the observation conditions were poor.

3. Results and discussion

Tables 1 and 2 give the CCD polarization data for comets Giacobini-Zinner and U5 (Linear), respectively. We list the date of observation, the central wavelength

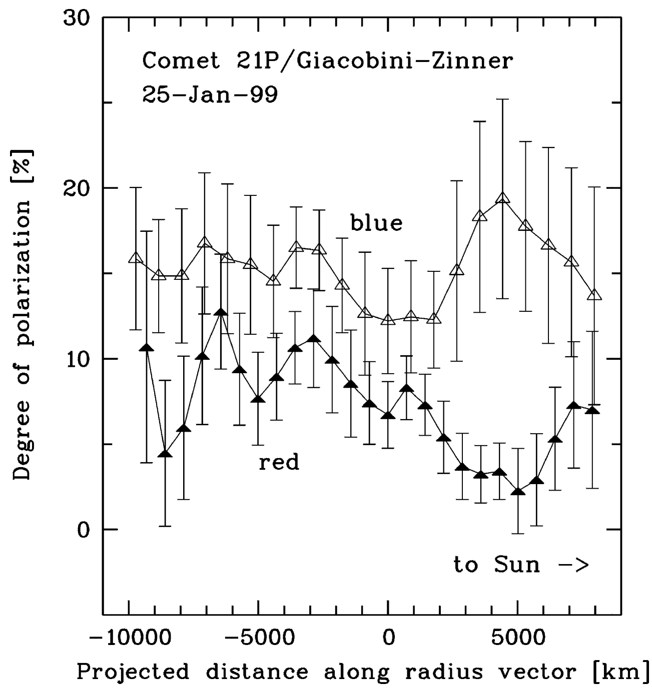

Fig. 1. Degree of polarization of comet 21P/Giacobini-Zinner plotted versus projected distance along the comet–Sun line as derived from imaging polarimetry obtained on January 25, 1999. The error bars are derived from the standard deviation in a box of 3 × 3 pixel surrounding the plotted value.

of the filter, the degree of polarization P and the position angle of polarization plane θ, including their statistical mean square errors σ_P and σ_θ, the size of area projected at the comet, the heliocentric and geocentric distances r and Δ of the comet, and the phase angle α. The errors of the degree of polarization of Comet Giacobini-Zinner were calculated from the statistics of counts for comet and background (Geyer et al., 1996). The accuracy of the measured polarization of Comet U5 (Linear) was found from statistics of the Stokes parameter q and u.

On November 20, 1998 the images of Comet Giacobini-Zinner, which were obtained simultaneously in four polarization directions, were slightly extended because of an improper setting of the cometary proper motion. Therefore, for this date we could only obtain the degree of polarization integrated over a large area of the coma, which was still free from star trails. On January 25, 1999 the moon caused a high sky background and the comet was rather faint. In Fig. 1, we present cuts along the comet–Sun line through the red and blue polarimetric images of this date. To decrease the noise the data were averaged over 3 × 3 pixel. The error bars are derived from the standard deviation found in these nine pixels. No significant spatial gradient can be noticed in Fig. 1. The averaged values shown in Table 1, however, are significantly less than the values in Fig. 1. This indicates that there is some decrease of polarization perpendicular to the comet–Sun line. The signal/noise ratio of the polarization image does

Table 1
CCD polarimetry of Comet 21P/Giacobini-Zinner

Data (UT)	Filter (λÅ)	P (%)	θ (deg)	r (AU)	Δ (AU)	α (deg)
			Area 35 300 × 32 200 km^2			
1998 Nov 20.651	4430	16.9 ± 0.4	160.1 ± 0.7	1.033	0.854	62.26
	6420	14.3 ± 0.3	155.0 ± 0.5			
			Area 15 050 × 15 050 km^2			
1999 Jan 25.710	4430	8.0 ± 1.4	149.5 ± 6	1.366	1.221	44.28
	6420	5.1 ± 0.6	136 ± 3			

Table 2
CCD polarimetry of Comet C/1998 U5 (Linear)

Data (UT)	Filter (λÅ)	P (%)	θ (deg)	r (AU)	Δ (AU)	α (deg)
			Area 7800 × 7800 km^2			
1998 Nov 24.872	4430	6.7 ± 0.3	172.1 ± 1.2	1.303	0.540	43.84
	6420	10.6 ± 0.3	0.8 ± 0.8			

not allow further conclusions about the spatial distribution of polarization.

The results of the aperture polarimetry of Comet Giacobini-Zinner are given in Table 3. Notations are the same as for Tables 1 and 2.

Fig. 2 presents our observations of both comets and the published polarimetric data for Giacobini-Zinner by Kurchakov et al. (1986) and Chernova et al. (1993). Observations of Kurchakov et al. were obtained with an aperture polarimeter at the 1-m telescope of Mountain Observatory (Kazakhstan) for the BC (4845/65 Å) and RC (6840/90 Å) continuum filters. Chernova et al. used the BC and wide-band R (6855/1080 Å) filters. For comparison, we added data for comets C/1987 P1 (Bradfield), C/1990 K1 (Levy) (Chernova et al., 1993) and C/1996 B2 (Hyakutake) (Kiselev and Velichko, 1998) for the BC and RC filters. One can see that the degree of polarization of Comet Giacobini-Zinner in the blue continuum is in agreement with that of comets Bradfield, Levy, Hyakutake, and U5 (Linear). At the same time the polarization of Giacobini-Zinner in the red filters is permanently lower (about 2%) than in the blue ones. As can be seen from Fig. 1, comets Bradfield, Levy, Hyakutake, and U5 (Linear) display a common property of all comets — the polarization increases with wavelength. In contrast to this, Giacobini-Zinner has an anomalous wavelength dependence of polarization. The difference between the polarization of Giacobini-Zinner and that of other comets is about 4% in the red wavelength domain. No other comet observed before showed a similar wavelength dependence of polarization. Simultaneous observations of comets

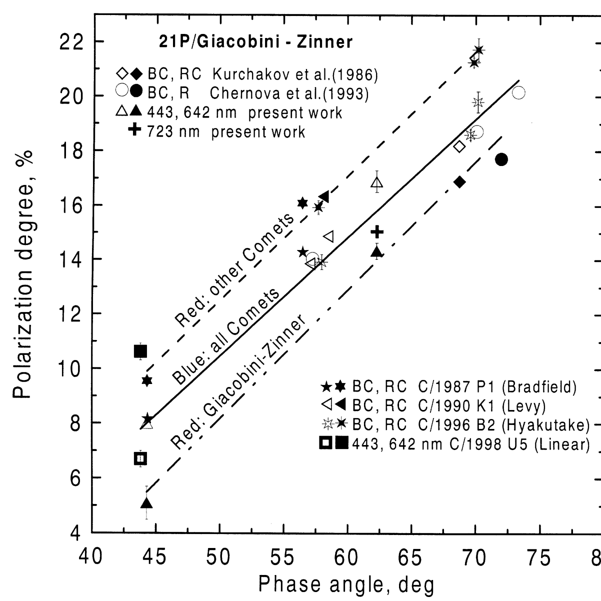

Fig. 2. Phase dependence of polarization of comets 21P/Giacobini-Zinner, C/1987 P1 (Bradfield), C/1990 K1 (Levy), C/1996 B2 (Hyakutake) and C/1998 U5 (Linear) for the blue (open symbols) and red (filled symbols) continuum filters. All comets display the same polarization in the blue spectral range (solid line). The polarization of Giacobini-Zinner in the red spectral range (dash-dotted line) is ≈ 2% less than in the blue range and ≈ 4% less than the polarization of the other comets in the red range (dashed line).

Giacobini-Zinner and U5 (Linear) and an identical procedure of reduction allow us to conclude that the effect observed for Giacobini-Zinner is not an instrumental one.

Table 3
Aperture polarimetry of Comet 21P/Giacobini-Zinner in the 7228/1140 Å filter

Date (UT) 1998	$P \pm \sigma_P$ (%)	$\theta \pm \sigma_\theta$ (deg)	Diaph. (km)	r (AU)	Δ (AU)	α (deg)
Nov 19.678	14.2 ± 0.7	160.5 ± 1.6	54 600	1.034	0.856	62.23
21.696	15.2 ± 1.4	164.8 ± 2.8	54 450	1.034	0.853	62.29
22.674	15.1 ± 0.3	162.9 ± 0.8	54 400	1.034	0.852	62.29

First, we consider whether the observed low polarization in the red filters is due to contamination by gas emissions. Kiselev et al. (1999) have shown that NH_2 emission at λ6408 Å and a weak unidentified emission at λ6428 Å fall within the red continuum filter (6420/28 Å) used for polarimetric observations. There is evidence that the polarization of NH_2 and H_2O^+ is very low (Jockers, 1997). The depolarization effect also depends on the relative contribution of emissions with respect to the continuum. Konno and Wyckoff (1989) and Beaver et al. (1990) have found that NH_2 was depleted in Giacobini-Zinner and its abundance was 5 times less than that in normal comets. The NH_2 $(0,8,0)$ λ6335 Å band is the strongest transition in the discussed wavelength region. Fink and Hicks (1996) provide fluxes of the (0,8,0) band of NH_2 and of a continuum window at 6250 Å of width 36 Å. From these data we find that the ratio of fluxes $F(NH_2)/F_c(6250)$ in Comet Giacobini-Zinner is about 0.13. One may estimate the depolarizing influence of NH_2 if the observation were carried out in a band pass at λ6335 Å of 36 Å width. For that we use the following equation:

$$P_{obs} = P_c \times F_c + P_{emi} \times F_{emi}, \tag{1}$$

where P_{obs} is the observed degree of polarization, P_{emi} the degree of polarization of emission and F_c and F_{emi} are fluxes of continuum and emission normalized to the total flux ($F_c + F_{emi} = 1$ and $F_{emi}/F_c = 0.13$). For $P_{obs} = 14.3\%$ (our result for the red filter), $F_c = 0.88$, $F_{emi} = 0.12$ and $P_{emi} = 1.5\%$ (Kiselev et al., 1999), the degree of polarization of the "clean" continuum P_c should be 16.0%. So, the maximal depolarization in the NH_2 (0,8,0) band is only 1.7%. For Comet Giacobini-Zinner all NH_2 bands, which pass through the filters λ6420/28 Å, RC, R and λ7228/1140 Å are much weaker than the NH_2 (0,8,0) emission band (see Fig. 4 in Fink and Hicks, 1996). According to Korsun (private communication), the flux ratio for the NH_2 (0,8,0) transitions to the NH_2 emission at λ6408 Å is about 30 for Comet C/1996 Q1 Tabur. Consequently, the reduced polarization of Comet Giacobini-Zinner observed in the narrow-band red filters cannot be explained by the NH_2 contamination. Not much can be said about the wide-band 7228/1140 Å filter.

A decrease of polarization in the BC filter may be caused by C_2 emission. According to A'Hearn et al. (1995), the relative production rates $Q(C_2)/Af\rho$ in Giacobini-Zinner are the same as in Comet C/1987 P1 (Bradfield). Therefore, both comets have the same contribution of C_2 in the BC filter and the same contribution of gas to the measured polarization. Comet Bradfield, however, has a positive wavelength gradient of polarization. The blue filter λ4430/44 Å also transmits a very weak unidentified emission (Kiselev et al., 1999) but its influence on polarization should be taken into consideration only for comets with very small continuum. Anyway, gas contamination in the blue filters will only enlarge the negative wavelength gradient found in Comet Giacobini-Zinner.

Thus, it seems reasonable to assume that the anomalous spectral dependence of polarization of Comet Giacobini-Zinner is caused by properties of its dust particles, which are different from those of other comets.

There is direct and indirect evidence that Comet Giacobini-Zinner differs from other comets. According to Beaver et al. (1990), Cochran and Barker (1987), and Schleicher et al. (1987), Comet Giacobini-Zinner belongs to the group of comets depleted of NH_2, C_2, C_3 and NH emissions. As was pointed out by Konno and Wyckoff (1989), the depletion of carbon in Giacobini-Zinner may be related to the low dust production rate. On the other hand, the gas-to-dust ratio varies considerably (more than two orders) among comets (A'Hearn et al., 1995), and Giacobini-Zinner is not an extreme case. Sanzovo et al. (1996) pointed out that Giacobini-Zinner has an intermediate dust-to-gas mass ratio.

The average colour BC−RC=0.24^m of Giacobini-Zinner is redder than that of Bradfield (0.07^m), Levy (0.13^m) (Kolokolova et al., 1997) and Hyakutake (0.18^m) (Kiselev and Velichko, 1998). The redder colour in Giacobini-Zinner may be caused by a large fraction of large particles. However, the redder colour can also be explained if the imaginary part of refractive index of dust particles decreases with wavelength (Kolokolova and Jockers, 1997).

Additional evidence for the difference of the dust particle properties of Giacobini-Zinner follows from the IR-photometry by Hanner et al. (1992). These authors have found a broad, weak silicate feature about 10% above the 10 μm continuum and concluded that a silicate-rich heterogeneous grain model with an excess of large particles is compatible with the observed spectrum of Giacobini-Zinner.

Evidence for unusual properties of dust in Comet Giacobini-Zinner was also obtained from the investigation of the Draconid meteors associated with this object. The Draconids have short atmospheric trajectories and disappear at abnormally great heights of ~100 km

(Wasson, 1985). Consequently, the meteor particles should be very fragile and quickly evaporated. Ceplecha (1977) had shown that the dust particles of the Draconid meteoroid stream are composed of soft material with an extremely low density of about 0.2 g cm^{-3}. Their composition is similar to that of carbonaceous chondrites, which consist of hydrated silicates, organic compounds and are depleted in carbon (Cronin et al., 1988). According to Lebedinets (1991), the Draconid meteor particles consist of 90% organic material. Wu and Williams (1995) and Ceplecha (1977) have shown that Giacobini-Zinner ejects a lot of large meteoroids.

These results are very important for our understanding of the anomalous wavelength dependence of polarization of Giacobini-Zinner. Kolokolova and Jockers (1997) have shown that the spectral dependence of polarization is mainly determined by the wavelength dependence of absorption index. According to this paper (see Fig. 4b), organic, graphite, astronomical silicate + organic and astronomical silicate + iron provide a negative value of $dP/d\lambda$. Only the pure astronomical silicate shows an increase of polarization with wavelength. Obviously, graphite and iron can be excluded from further consideration. Most probably, organic or astronomical silicate + organic is the main component of dust particles of Comet Giacobini-Zinner.

As a second important factor determining the wavelength gradient of polarization, Kolokolova and Jockers mention the particle size distribution. In the case of Comet Giacobini-Zinner an unusually high abundance of large particles may cause, or at least contribute to, the negative gradient of polarization.

4. Conclusion

The results of CCD and photoelectric polarimetry of Comet Giacobini-Zinner and CCD polarimetry of Comet C/1998 U5 (Linear) have been given. It is shown that the degree of polarization of Giacobini-Zinner is in a good agreement with that of comets Bradfield, Levy, Hyakutake and U5 (Linear) in the blue continuum filters. At the same time, polarization of Giacobini-Zinner in the red domain is about 2% less than that in the blue wavelength range and is about 4% less than the polarization of other comets in the red range. Thus, the spectral trend of polarization for Giacobini-Zinner is opposite to the wavelength dependence of polarization usually observed in comets. It was shown that the molecular emission present in the continuum filters cannot produce such an effect. We attribute the negative wavelength gradient of polarization of Comet Giacobini-Zinner to a higher content of organic material in its dust particles or to an overabundance of large particles.

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